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Program Analysis and Integration Center

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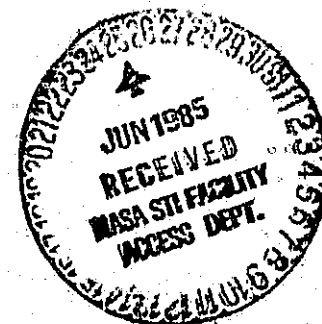
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Documents of the JPL Photovoltaics Program Analysis and Integration Center

An Annotated Bibliography

A.M. Pearson



April 1, 1985

Prepared for
U.S. Department of Energy
Through an Agreement with
National Aeronautics and Space Administration
by

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ABSTRACT

A bibliography of internal and external documents produced by the Jet Propulsion Laboratory, based on the work performed by the Photovoltaics Program Analysis and Integration Center, is presented with annotations. As shown in the Table of Contents, the bibliography is divided into three subject areas: (1) Assessments, (2) Methodological Studies, and (3) Supporting Studies.

FOREWORD

In the middle of calendar year 1983, the Jet Propulsion Laboratory, after discussions with the National Photovoltaics Program manager at the U.S. Department of Energy (DOE), phased out the Photovoltaics Technology Development and Applications Lead Center and phased in the Photovoltaics Program Analysis and Integration (PA&I) Center. The role of the latter was stated by DOE:

The role of the Program Analysis and Integration (PA&I) Center is to provide multiyear planning, analysis and integration complementing Headquarters in their management of the PV Program. The PA&I Center will continue to participate in reviews of Photovoltaics Program progress, and will prepare specific issue papers and selected studies, as well as analyses of existing PV program studies. A conspicuous character of this analysis will be to address cross-cut issues that involve multiple research centers. The PA&I Center will also facilitate technology transfer activities.

During the approximately 18 months of its existence, the PA&I Center performed a number of studies and analyses. This report is an annotated bibliography of informal or formal documents based on the work performed.

The bibliography is divided into three subject areas:

1. Assessments
2. Methodological Studies
3. Supporting Studies

The table of contents lists the reports that are included in this bibliography.

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SECTION I

ASSESSMENTS

Borden, C.S., Relative Potentials of Concentration and Two-Axis Tracking Flat-Plate Photovoltaic Arrays for Central-Station Applications, JPL Publication 85-16, JPL Document No. 5230-15, Jet Propulsion Laboratory, Pasadena, California, December 31, 1984.

The purpose of this study is to assess the relative economic potential of concentrating and two-axis tracking flat-plate photovoltaic (PV) arrays for central-station applications in the mid-1990's. Specific objectives of this study are to provide information on concentrator photovoltaic collector probabilistic price and efficiency levels to illustrate critical areas of R&D for concentrator cells and collectors, and to compare concentrator and flat-plate PV price and efficiency alternatives for several locations, based on their implied cost of energy. To deal with the uncertainties surrounding research and development activities in general, a probabilistic assessment of commercially achievable concentrator photovoltaic collector efficiencies and prices (at the factory loading dock) is performed. The results of this projection of concentrator photovoltaic technology are then compared with a previous flat-plate module price analysis (performed early in 1983). To focus this analysis on specific collector alternatives and their implied energy costs for different locations, similar two-axis tracking designs are assumed for both concentrator and flat-plate options. The results of this study provide the first comprehensive assessment of PV concentrator collector manufacturing costs in combination with that of flat-plate modules, both projected to their commercial potential in the mid-1990's.

Borden, C.S., The Value of Residential Photovoltaic Systems: A Comprehensive Assessment, JPL Publication 83-63, JPL Document No. 5220-19, Jet Propulsion Laboratory, Pasadena, California, September 15, 1983.

Utility-interactive PV arrays on residential rooftops appear to be a potentially attractive, large-scale application of PV technology. Results of a comprehensive assessment of the value (i.e., break-even cost) of utility-grid connected residential photovoltaic power systems under a variety of technological and economic assumptions are presented. A wide range of allowable PV system costs (\$1 to \$3 per peak watt) are calculated for small (4.34 kW_p ac) residential PV systems in various locales across the United States. Primary factors in this variation are differences in local weather conditions; utility-specific electric generation capacity, fuel types, and customer-load profiles that affect purchase and sell-back rates; and non-uniform state tax considerations.

Additional results from this analysis are: locales that have the highest insolation values are not necessarily the most economically attractive sites; residential PV systems connected in parallel to the utility demonstrate high percentages of energy sold back to the grid, and owner financial and tax assumptions cause large variations in break-even costs. Significant cost reduction and aggressive resolution of potential institutional impediments (e.g.,

liability, standards, metering, and technical integration) are required for a residential PV market to become a major electric-grid-connected energy-generation source.

Costogue, E.N., Ferber, R.R., Lutwack, R., Lorenz, J.H. (JPL Consultant), and Pellin, R. (JPL Consultant), Polycrystalline Silicon Study, Low-Cost Silicon Refining Technology Prospects and Semiconductor-Grade Polycrystalline Silicon Availability through 1988, JPL Publication 84-41, JPL Document No. 5230-12, Jet Propulsion Laboratory, Pasadena, California, May 30, 1984.

Photovoltaic arrays that convert solar energy into electrical energy can become a cost-effective bulk energy generation alternative, provided that an adequate supply of low-cost materials is available. One of the key requirements for economic photovoltaic cells is reasonably priced silicon.

At present, the photovoltaic industry is dependent upon polycrystalline silicon refined by the Siemens process primarily for integrated circuits, power devices, and discrete semiconductor devices. This dependency is expected to continue until low-cost silicon refining technology developments sponsored by the U.S. Department of Energy (DOE) have matured to the point where they are in commercial use. The photovoltaic industry can then develop its own source of supply.

Since 1979 the Jet Propulsion Laboratory Technology Development and Applications Lead Center (TD&A), now the Program Analysis and Integration (PA&I) Center, has periodically examined the availability of refined silicon and the status of DOE-sponsored low-cost silicon refining technology developments. Three reports have been published, based on surveys conducted by JPL consultants in 1979, 1981, and 1983.

This report updates the silicon material availability and market pricing projections through 1988, based on data collected early in 1984. It also presents an overview of silicon refining industry plans to meet the increasing demands of the semiconductor-device and photovoltaic-product industries. A section of the report has been devoted to review of the DOE-sponsored technology research for producing low-cost polycrystalline silicon, probabilistic cost analysis for the two most promising production processes for achieving the DOE cost goals, and the impacts of National Photovoltaics Program silicon-refining research upon the commercial polycrystalline-silicon refining industry.

Effects of Expiration of the Federal Energy Tax Credit on the National Photovoltaics Program, JPL Publication 84-36, JPL Document No. 5220-23, Jet Propulsion Laboratory, Pasadena, California, May 1984.

The Federal energy tax credit is scheduled to expire at the end of 1985. This study concludes that the U.S. photovoltaic manufacturing industry will be hurt by the expiration. Projected 1986 sales are significantly reduced as a

direct result of system price increases resulting from expiration of the credits. The character of the industry will probably change, with greatly reduced emphasis on domestic electric-utility applications. Indirect effects arising from unrealized economies of scale and reduced private investment in PV research and development (R&D) and in production facilities could have a very large cumulative adverse impact on the U.S. PV industry. The industry is forecasting as much as a fourfold reduction in 1990 sales if tax credits expire, compared with what sales would be with the credits. Because the National Photovoltaics Program is explicitly structured as a government industry partnership, large changes in the motivation or funding of either partner can affect Program success profoundly. In particular, reduced industry participation implies that such industry tasks as industrialization and new-product development will be slowed or even halted. In addition, those PV research areas receiving heavy R&D support from private PV manufacturers, such as collector research, module reliability, and some balance-of-system development and large-system experiments, will be adversely affected due to reduced private participation and funding. Finally, the curtailment of electric utility applications will delay realization of photovoltaics as an important U.S. bulk power option.

Ferber, R.R., Costogue, E.N., and Shimada, K., Multijunction Cells for Concentrators: Technology Prospects, Issue Study, JPL Publication 84-71, JPL Document No. 5230-13, Jet Propulsion Laboratory, Pasadena, California, November 15, 1984.

Development of high-efficiency multijunction solar cells for concentrator applications is a key step in achieving the goals of the U.S. Department of Energy National Photovoltaics Program. This report summarizes findings of an issue study conducted by the Jet Propulsion Laboratory Photovoltaic Analysis and Integration Center, with the assistance of the Solar Energy Research Institute and Sandia National Laboratories, which surveyed multijunction cell research for concentrators undertaken by federal agencies and by private industry. The team evaluated the potentials of research activities sponsored by DOE and by corporate funding to achieve projected high-efficiency goals, and developed summary statements regarding industry expectations. Recommendations are made for the direction of future work to address specific unresolved aspects of multijunction cell technology.

Shimada, K., Silicon Sheet and Thin-Film Cell and Module Technology Potential, JPL Publication 84-95, JPL Document No. 5230-14, Jet Propulsion Laboratory, Pasadena, California, February 1985.

The development of high-efficiency low-cost crystalline silicon ribbon and thin-film solar cells is a key element in achieving the goals of the U.S. Department of Energy National Photovoltaics Program. This report summarizes the findings of an issue study conducted by the Photovoltaics Program Analysis and Integration Center at the Jet Propulsion Laboratory, with assistance from the Solar Energy Research Institute and the Flat-Plate Solar Array Project at

the Jet Propulsion Laboratory. The study team interviewed leading researchers in crystalline-silicon ribbon and thin-film solar-cell technologies from Federal agencies and industry that conduct research funded both by the government and by private investment. The collected data identified the status of the technology, future research needs, and problems experienced. The data were also studied and evaluated to assess the potentials of present research activities to meet the Federal-industry long-term technical goal of achieving 15¢ per kilowatt-hour levelized PV energy cost. Recommendations for future research needs related to crystalline silicon ribbon and thin-film technologies for flat-plate collectors are included.

Zimmerman, L.W., and Smith, J.L., Sensitivities of Projected 1990 Photovoltaic System Costs to Major System Cost Drivers, JPL Publication 84-93, JPL Document No. 5220-28, Jet Propulsion Laboratory, Pasadena, California, December 15, 1984.

This report examines the sensitivity of projected 1990 photovoltaic system costs to major system cost drivers, including (1) module costs and module efficiencies, (2) area-related balance-of-system (BOS) costs, (3) inverter costs and efficiencies, and (4) module marketing and distribution markups and system integration fees. The report reviews recent PV system cost experiences, illustrating the high costs of electricity from the systems. Based on a review of selected PV engineering literature, 1990 system costs are then projected for five classes of PV systems, including four ground-mounted 5-MW_p systems and one residential 5-kW_p system. System cost projections are derived by first projecting costs and efficiencies for all subsystems and components. Sensitivity analyses reveal that reductions in module cost (including marketing markups) and engineering and system integration fees seem to have the greatest potential for contributing to system cost reduction. Although module cost is clearly the prime candidate for fruitful PV research and development activities, engineering and system integration fees seem to be more amenable to reduction through appropriate choice of system size and marketing and distribution strategy. Inverter costs are not as significant to total system costs as are other cost categories, but increases in inverter and module efficiency yield significant benefits, especially for systems with high area-related costs.

SECTION II

METHODOLOGICAL STUDIES

Borden, C.S., Volkmer, K., Cochrane, E.H., and Lawson, A.C., Stand-Alone Flat-Plate PV Power Systems-System Sizing and Life Cycle Costing Methodology for Federal Agencies, JPL Publication 84-37, JPL Document No. 5260-32, Jet Propulsion Laboratory, Pasadena, California, May 1984.

A simple methodology to estimate photovoltaic system size and life-cycle costs in stand-alone applications is presented in this document. It is designed to assist engineers at Government agencies in determining the feasibility of using small stand-alone photovoltaic systems to supply ac or dc power to the load. Photovoltaic system design considerations are presented, as are the equations for sizing the flat-plate array and the battery storage to meet the required load. Cost effectiveness of a candidate photovoltaic system is based on comparison with the life-cycle cost of alternative systems. Examples of alternative systems addressed herein are batteries, diesel generators, the utility grid, and other renewable energy systems.

Cochrane, E.H., Lawson, A.C., and Savage, C.H., Flat-Plate PV Power Systems Handbook for Federal Agencies, JPL Publication 84-35, JPL Document No. 5260-33, Jet Propulsion Laboratory, Pasadena, California, April 1984.

The Federal Photovoltaic Utilization Program (FPUP), sponsored by the Department of Energy, has provided an opportunity for 26 Federal agencies to install photovoltaic power systems in various types of applications and environments. As the cost of photovoltaic power is reduced, an increasing number of potential, terrestrial, photovoltaic applications become costeffective within these agencies. Certain Federal agencies have additional criteria for the use of photovoltaic power systems such as silent operation, reliable power, and independence from the limited availability of grid power of a host country.

The primary purpose of this handbook is to provide a tool for personnel in Federal agencies to evaluate the viability of potential photovoltaic applications. A second objective is to provide descriptions of various photovoltaic systems installed by different Federal agencies under the Federal Photovoltaic Utilization Program so that other agencies may consider similar applications. A third objective is to share lessons learned, which are presented throughout the document, to enable more effective procurement, design, installation, and operation of future photovoltaic systems. The intent of this publication is not to provide a complete handbook, but rather to provide a guide for Federal agency personnel, with additional information incorporated in references.

This handbook has been organized to present the steps to be followed in selecting, procuring, and installing a photovoltaic application. It is based on lessons learned from FPUP as well as on an overview of existing FPUP applications.

Davissan, M.S., Borden, C.S., Reiter, L.J., and Smith, J.H., Lifetime Cost and Performance Model--Microcomputer Version User's Guide and Documentation, JPL Internal Document No. 5220-20, JPL D-944, Jet Propulsion Laboratory, Pasadena, California, August 15, 1983.

This report provides all necessary information to use the microcomputer implementation of the Lifetime Cost and Performance (LCP) model. The LCP is used to simulate the energy output, cost, and value of a photovoltaic power plant over its useful lifetime. A number of fixed and tracking flat-plate PV array alternatives are available for evaluation. Costs incurred while constructing and operating the PV plant are incorporated as well as revenues from the sale of energy by a non-utility owner to a utility, or fuel and operating costs avoided by a utility by not generating electricity using conventional plants.

In addition to the energy-output-related costs and benefits, monthly recurrent operations and maintenance expenses occur throughout the lifetime of the PV plant. These costs include cleaning of the modules on a preselected schedule, monitoring, and custodial activities that must take place to keep the system operating.

The remainder of this document is a practical guide to developing inputs for case studies and for program use.

Reiter, L.J., Borden, C.S., Smith, J.L., and Zimmerman, L.W., Rating Methods for Flat-Plate and Concentrator Photovoltaic Modules and Systems, JPL Internal Document No. 5220-27, JPL D-1805, Jet Propulsion Laboratory, Pasadena, California, October 15, 1984.

Methods of rating photovoltaic modules and systems are reviewed, selected and refined in this study. The various existing and proposed methods of rating flat-plate and concentrator modules and PV systems are discussed, as are many of the underlying issues and criteria that affect the choice of rating schemes. A module rating method based on a standard set of peak conditions is recommended. It is also recommended that PV systems be rated at a set of peak conditions specific to the site in which the system will be installed.

Smith, J.H., and Reiter, L.J., Summary of Photovoltaic System Performance Models, JPL Publication 84-4, JPL Document No. 5220-22, Jet Propulsion Laboratory, Pasadena, California, January 15, 1984.

The purpose of this study is to provide a detailed overview of photovoltaics (PV) performance modeling capabilities that have been developed during recent years for analyzing PV system and component design and policy issues.

A set of performance modeling topics and characteristics is defined and used to examine some of the major issues associated with photovoltaic performance modeling. Each of the models is described in the context of these topics and characteristics to assess its purpose, approach, and level of detail. Then each of the issues is discussed in terms of the range of model capabilities available and summarized in tabular form for quick reference. Finally, the models are grouped into categories to illustrate their purposes and perspectives.

System Experiment Selection Strategy: A Methodology for the Rational Selection of System Level Experiments, JPL Internal Document No. 5240-14, JPL D-773, Jet Propulsion Laboratory, Pasadena, California, July 1983.

The objective of the DOE Photovoltaics Program is to advance scientific understanding and enlarge the technology base needed for the private sector to develop and utilize advanced photovoltaic energy systems in the United States. The Photovoltaics Program will support research and development of photovoltaic technology that is potentially capable of competitive application in bulk electricity markets, thereby promoting a major new energy source for the United States. This technology involves grid-connected applications only and can be divided into small, roof-mounted systems and large, ground-mounted systems. To meet this program objective, it is necessary to develop systems and test critical system components and their interactions in experimental systems.

The National Photovoltaics Program must provide enough information (sufficient technology base) regarding all facets of performance to reduce risk to the private sector; this cannot be accomplished without a balanced program including system-level experiments. A system-level experiment is defined as an experiment that contains two or more subsystems, and is designed to evaluate the interface between those subsystems.

Volkmer, K., Nomographs for Estimating the Levelized Cost of Energy from Flat-Plate and Concentrator Photovoltaic Systems, JPL Publication 85-19, JPL Document No. 5240-13, Jet Propulsion Laboratory, Pasadena, California, December 31, 1984.

A set of nomographs to estimate the levelized energy cost for photovoltaic systems are presented. These are designed to assist system designers, analysts, and planners in estimating the effects of research and development and system-design optimization on the delivered cost of energy. The nomographs are based on a refined version of the energy cost estimation equation that appears in the National Photovoltaics Program Five-Year Research Plan. The nomographs have been prepared to emphasize technologies with the potential of producing low-cost energy ($<0.40/\text{kWh}$), and thus primarily apply to far-term or advanced intermediate photovoltaic technologies. Separate sets of nomographs are presented to encompass both flat-plate and concentrator technologies. To supplement the nomographs, a set of tabular solutions of the energy cost equation are included as an appendix.

SECTION III

SUPPORTING STUDIES

Module Utilization Committee Final Report, JPL Publication 84-40, JPL Document No. 5220-24, Jet Propulsion Laboratory, Pasadena, California, March, 1984.

Photovoltaic collector modules were declared surplus to the needs of the U.S. Department of Energy. The Module Utilization Committee was formed to make appropriate disposition of the surplus modules. The final report of that committee documents that disposition. The membership and activities of the committee are set forth and the results of its activities are reported.

Patterns of In-House and Procurement Expenditures for Laboratories Supporting the National Photovoltaics Program, Issue Study, JPL Internal Document No. 5210-29, JPL D-1943, Jet Propulsion Laboratory, Pasadena, California, November 15, 1984.

The Photovoltaics PA&I Center at JPL initiated this study in response to a DOE request for data on the allocation of PV program funds between in-house and external procurement work at each of the three participating laboratories (JPL; Sandia National Laboratories, Albuquerque; and the Solar Energy Research Institute). Specifically, the PA&I Center was asked to examine the ratio of in-house to procurement (contract and vendor) expenditures. The first step was a literature search to determine if other studies in PV program funds disbursement had been conducted and if management guidelines existed on allocation of program funds. The literature search yielded neither previous studies nor guidelines.

Survey information on contract management data yielded interesting results. The three laboratories took differing approaches to contract management; JPL devoted more resources to this effort than did SNLA and SERI. However, at each of the three organizations the contract management effort was a small fraction of total PV program expenditures.

Conclusions of this study are: (1) No previous studies or supportable appropriate guidelines exist regarding in-house versus procurement expenditure ratios. (2) Each laboratory expends funds and work years in essentially the same areas of work, though the amount expended in each area varies. The survey did not gather enough data to determine the nature of the variations among the laboratories. However, the unique character of the work performed at each laboratory, combined with possibly different management practices and overhead accounting structures, may explain these variances. (3) In-house expenditures for testing in support of industry should be treated as a procurement expenditure. This part of the testing program is carried out in support of industry's role in the National Photovoltaics Program.

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Reliability of Photovoltaic Modules: An Issue Paper, JPL Internal Document No. 5250-19, JPL D-945, Jet Propulsion Laboratory, Pasadena, California, August 8, 1983.

This document reports results of a study requested by the U.S. Department of Energy Photovoltaics Program Office. The request involved the pros and cons of a federally sponsored effort to assess the reliability of commercially available photovoltaic modules. Study participants were drawn from the JPL Flat-Plate Solar Array Project, the Solar Energy Research Institute and Sandia National Laboratories, Albuquerque.

The results of the study include a recommendation to establish a reliability assessment program for modules installed in large-scale system experiments, augmented where appropriate, by data from privately funded field installations. Actions should be taken in planning such an activity to gain industry support for the effort. Data dissemination should be carried out in such a way as to avoid undue damage to manufacturer's reputations.

What Should DOE Do to Help Establish Voluntary Consensus Standards for Measuring and Rating the Performance of PV Modules?, Issue Study, JPL Publication 84-73, JPL Document No. 5220-30, Jet Propulsion Laboratory, Pasadena, California, October 31, 1984.

In response to concern expressed by the photovoltaics community over progress toward the establishment and issuance of consensus standards on photovoltaic performance measurements, a review of the status of and progress in developing these standards was conducted. It examined the roles of manufacturers, consumers and the national laboratories funded by the U.S. Department of Energy in supporting this effort. This was done by means of a series of discussions with knowledgeable members of the photovoltaic community.

Results of these interviews are summarized and a new approach to managing support of standards activity that responds to specific problems found in the performance measurement standards area is recommended.

The study concludes that there is a positive role to be played by the U.S. Department of Energy in establishing collector performance measurement standards. It recommends that DOE continue to provide direct financial support for selected committees and for research at national laboratories, and that management of the activity be restructured to increase the authority and responsibility of the consensus committee.

Volkmer, K., Photovoltaics Program Planning Data Base: A Tool to Assist in Decision Making, JPL Document No. 5220-26, JPL D-1634, Jet Propulsion Laboratory, Pasadena, California, January 31, 1985.

A data base has been developed that provides a summary description of all technical activities in the National Photovoltaics Program. The data base has

been structured to provide Program management with comprehensive information on Program status and issues that will facilitate assessment of current priorities and will support future Program planning. The format has been designed to accommodate frequent updating of appropriate sections. The data base partitions the Program into 21 paths of action that represent separate areas of activity. For each path of action, the data base describes objectives, rationale, Program policies, implementation plan, status, and budget impact. In addition, the status of private-sector activity in the area represented by the path of action is summarized, and both technical and programmatic issues are noted. For convenience, these issues have been collected into a single section in the Introduction.

Pearson, A.M., Documents of the JPL Photovoltaics Program Analysis and Integration Center: An Annotated Bibliography, JPL Document No. 5210-22, JPL Publication 85-26, Jet Propulsion Laboratory, Pasadena, California, April 1, 1985.

A bibliography of internal and external documents produced by the Jet Propulsion Laboratory, based on the work performed by the Photovoltaics Program Analysis and Integration Center, is presented with annotations. As shown in the Table of Contents, the bibliography is divided into three subject areas: (1) Assessments, (2) Methodological Studies, and (3) Supporting Studies.

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